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Physical Modeling of Scaled Water Distribution System Networks

Lee Orear, Glenn Hammond, Sean McKenna, Paul Molina, Ross Johnson, Tim O'Hern, Bart van Bloemen Waanders

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Physical Modeling of Scaled Water Distribution System Networks

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ABSTRACT

Threats to water distribution systems include release of contaminants and Denial of Service (DoS) attacks. A better understanding, and validated computational models, of the flow in water distribution systems would enable determination of sensor placement in real water distribution networks, allow source identification, and guide mitigation/minimization efforts. Validation data are needed to evaluate numerical models of network operations. Some data can be acquired in real-world tests, but these are limited by 1) unknown demand, 2) lack of repeatability, 3) too many sources of uncertainty (demand, friction factors, etc.), and 4) expense. In addition, real-world tests have limited numbers of network access points. A scale-model water distribution system was fabricated, and validation data were acquired over a range of flow (demand) conditions. Standard operating variables included system layout, demand at various nodes in the system, and pressure drop across various pipe sections. In addition, the location of contaminant (salt or dye) introduction was varied. Measurements of pressure, flowrate, and concentration at a large number of points, and overall visualization of dye transport through the flow network were completed. Scale-up issues that that were incorporated in the experiment design include Reynolds number, pressure drop across nodes, and pipe friction and roughness. The scale was chosen to be 20:1, so the 10 inch main was modeled with a 0.5 inch pipe in the physical model. Controlled validation tracer tests were run to provide validation to flow and transport models, especially of the degree of mixing at pipe junctions. Results of the pipe mixing experiments showed large deviations from predicted behavior and these have a large impact on standard network operations models.

CONTENTS

FIGURES

TABLES

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Ensuring the physical security of municipal water distribution systems has recently become a national priority. A number of different projects are currently underway at Sandia as well as other agencies (e.g., EPA) to examine different aspects of water distribution system security. These studies currently lack a readily accessible water distribution network to conduct physical experiments that can emulate different types of attacks on the system.

Two potential physical attacks on water distribution systems are 1) introduction of chemical-biological-radioactive contamination into the distribution network and 2) denial of service (DoS) attacks which physically remove nodes from the system. Experimental data for either type of attack are unavailable and extremely difficult to acquire at present. Field tests are expensive, difficult to run, and nearly impossible to repeat. Contaminant attacks can be approximated by introducing a benign tracer into the network and monitoring its movement through the system. However, these experiments are costly to field and require a considerable amount of regulatory permitting to accomplish. The resources necessary to field a tracer test make multiple tests on different parts of the system, or even repeating a single experiment under different conditions, impractical. DoS attacks can be tested in the field as well, generally by opening hydrants to approximate breaks in the system. These types of field tests require a large effort to perform and can waste considerable amounts of water. Another undesirable aspect of field testing is that measurements of water quality and flow properties of the water distribution system can only be accessed at a finite number of points through manholes and fire hydrants.

At the time that this project was undertaken, there were no known, readily available and flexible scaled physical experimental models of water distribution systems. Such a capability was developed and demonstrated under this project.

INTRODUCTION

Threats to water distribution systems include release of contaminants and Denial of Service (DoS) attacks. A better understanding, and validated computational models, of the flow in water distribution systems would enable determination of sensor placement in real water distribution networks, allow source identification, and guide mitigation/minimization efforts. Validation data are needed to evaluate numerical models of network operations. Some data can be acquired in real-world tests, but these are limited by 1) unknown demand, 2) lack of repeatability, 3) too many sources of uncertainty (demand, friction factors, etc.), and 4) expense. In addition, real-world tests have limited numbers of network access points. A scale-model water distribution system was fabricated, and validation data were acquired over a range of flow (demand) conditions. Standard operating variables included system layout, demand at various nodes in the system, and pressure drop across various pipe sections. In addition, the location of contaminant (salt or dye) introduction was varied. Measurements of pressure, flowrate, and concentration at a large number of points, and overall visualization of dye transport through the flow network were completed. Scale-up issues that that were incorporated in the experiment design include Reynolds number, pressure drop across nodes, and pipe friction and roughness. The scale was chosen to be 20:1, so the 10 inch main was modeled with a 0.5 inch pipe in the physical model. Controlled validation tracer tests were run to provide validation to flow and transport models, especially of the degree of mixing at pipe junctions. Results of the pipe node mixing experiments showed large deviations from predicted behavior. This finding is expected to have a large impact on standard network operations models.

There were two aspects to this project, first the testing of mixing in single pipe junctions (single-joint) and second the design, development, and testing of a pipe network.

Even though this was a relatively small project, it was possible to bring expertise from across Sandia to bear on the problem of constructing the laboratory facility, running the experiments and modeling the results of the experiments. Additionally, two students from the University of New Mexico participated in the construction and experimentation. The team members and their respective roles within the project are shown in Table 1.

Table 1. List of project team members (in alphabetical order)

Name	Organization	Roles
Ray Finley	6115	PM
Glenn Hammond	6115	Experimentation and numerical modeling
Ross Johnson	UNM	Construction and experimentation
Sean McKenna	6115	Documentation and experimentation
Paul Molina	UNM	Construction and experimentation
Tim O'Hern	1512	PI, Scaling calculations, experimental
Lee Orear	6115	Construction and experimental lead
Bart van Bloemen Waanders	1411	Numerical modeling and experimentation

CONSTRUCTION

The construction of the experimental apparatus was done in two distinct phases. The first phase was to construct the equipment for running the single-joint experiments and the second phase was the construction of the scaled water distribution network. Some equipment, e.g., the supply and effluent tanks and the pumps were used in both sets of experiments. Prior to any construction, a set of scaling calculations was completed to determine what experimental parameters could be achieved with different pipe diameters. The physical scaling considerations and design and construction details are given below.

PHYSICAL SCALING

Scale models have been used for many years to test fluid flow geometries and to acquire data on the flow properties in smaller, more controllable systems, for applications ranging from aircraft and naval design to river bank erosion. In order to determine when the scale model provides a useful simulation of the full-scale system, scaling laws must be developed for the flow of interest and their adherence determined. For flow in a water distribution network, the critical parameters are the pipe Reynolds number, friction factor, the pressure drop in nodes and across various pipe sections, and possibly the pipe roughness. In order to satisfy these scaling parameters, careful experimental design was done so that the appropriate dimensionless parameters were either matched or at least in the correct range so that the flow in the scale model will behave similarly to that in a real pipe network. Initial experiments included scaling studies on a small pipe module so that the scaling relations could be experimentally verified. This also provided a convenient testbed for conducting specific small scale experiments before building the final model, i.e. testing out scaling relationships, testing node behavior, testing measurement equipment, testing dyes and other contaminant detection, and matching simulation models for similar small scale sections. The pipe network was designed to have a modular structure to make these types of scaling studies easy to accomplish.

In real water distribution systems, pipe diameters are typically 8 to 12 inches, pressures are 80 to 120 psi and flow velocities are 3 to 5 ft/sec (Clark et al., 1977). Smaller pipes branch off of this main network to feed individual homes but are not included in models or seen as major threat locations and therefore were not included in the scale model. Table 2 lists the scaling factors taken into consideration for an isothermal pipe flow network. Geometric scaling determines the model-to-full scale ratio, in this case determined by the ratio of pipe diameters D_{lab}/D_{full}. The Reynolds number (Re) is a dimensionless parameter given by the ratio of momentum to viscous forces in a fluid flow. Generally, high Reynolds number flows are turbulent and low Reynolds number flows are laminar. In pipe flows the Reynolds number for transition to turbulence is usually on the order of 2000, depending somewhat on the level of disturbances in the flow. In a real water distribution system the pipe Reynolds number would typically range from 50000 to 300000 or more. The velocity in a small scale model would have to be increased in order to match Reynolds number with a real world distribution system, assuming the same working fluid (water) was used. In order to run higher velocities in the scale model, the time scale of the experiment will be greatly reduced from those of the full scale network. For 20:1 scaling, events that would take one hour in the real world system would take approximately 9 seconds in the scale model. This places undue burdens on the data acquisition speed. A trade-off can be made, allowing the velocity to be lowered so that the model Reynolds number becomes lower than the full scale Reynolds number, so long as the flow in the pipes remains turbulent. This is a common trade-off in running scale model experiments and is generally not problematic since the turbulent flow behavior does not change significantly with increasing Re, so long as Re is high enough to achieve a fully turbulent state. The goal of these experiments is to examine flow in the pipe network, so reduced contact time with the pipe walls caused by higher velocities in the model flow should not be an issue.

Table 2. Scaling parameters for contaminant transport in a water distribution system.

	Lab scale	**Full Scale**	**Ratio**
Mean Velocity (m/s)	U_{lab}	U_{full}	$\frac{U_{lab}}{U_{full}}$
Pipe Diameter (m)	D_{lab}	D_{full}	$\frac{D_{lab}}{D_{full}}$
Flowrate (m^3/s)	$Q_{lab} = U_{lab} \times \frac{\pi D_{lab}^2}{4}$	$Q_{full} = U_{full} \times \frac{\pi D_{full}^2}{4}$	$\frac{Q_{lab}}{Q_{full}} = \left(\frac{U_{lab}}{U_{full}}\right)\left(\frac{D_{lab}^2}{D_{full}^2}\right)$
Time (s)	$\tau_{lab} = \frac{D_{lab}}{U_{lab}}$	$\tau_{full} = \frac{D_{full}}{U_{full}}$	$\frac{\tau_{lab}}{\tau_{full}} = \left(\frac{U_{full}}{U_{lab}}\right)\left(\frac{D_{lab}}{D_{full}}\right)$
Reynolds Number	$\mathrm{Re}_{lab} = \frac{D_{lab}U_{lab}}{\nu}$	$\mathrm{Re}_{full} = \frac{D_{full}U_{full}}{\nu}$	$\frac{\mathrm{Re}_{lab}}{\mathrm{Re}_{full}} = \left(\frac{U_{lab}}{U_{full}}\right)\left(\frac{D_{lab}}{D_{full}}\right)$

Velocity is critical in determining the expected pressure drop per section of pipe. Smooth plastic pipe has a low friction factor (~0.01 for 1 inch pipe) so pressure drops for typical lab pipe runs between nodes of 2 to 5 foot spacing are very small, on the order of thousandths of a psi at low velocity values corresponding to Re = 2000, and increasing to tenths of a psi at the higher velocity values corresponding to Re = 50000.

SINGLE-JOINT SETUP

The experimental apparatus for the single-joint experiments was constructed such that different joint configurations, both double-T and cross, could be run using the same pumps and supply and effluent tanks. PVC pipe in ½, 1 and 2” diameter sizes was used. Transparent PVC was used for the ½” pipe experiments and white PVC was used for all other experiments. The joint components were always constructed of white PVC.

The inlet and outlet pipes were designed to be long enough to ensure complete mixing within the pipe as the tracer and fresh water moved from the supply tanks to the joint. The tracer tank is continuously mixed by recirculating some of the supply through the pump and back into the tank. The effluent pipes were sampled through small sampling ports near the downstream end of the pipes. The pressure in the system is controlled by a pair of pumps that inject both the tracer water and the fresh water into the supply pipes. The pressure between the two supply pipes is equalized using a differential manometer.

For all experiments, NaCl was mixed with water in the tracer supply tank. The amount of NaCl added was enough to raise the electrical conductivity of the tracer solution to be two to four times that of the fresh water. Blue dye (Warner-Jenkinson FD&C Blue No. 1) was also added to the tracer supply tank to allow for an easy visual assessment of the tracer test results. The tanks with the tracer and fresh water are shown in Figure 1. The blue dye makes the tracer visible during the experiment and in the samples obtained at the downstream end of the experiment (Figure 2). The samples are collected into beakers from the ports on the downstream pipes. Each beaker is filled within several seconds and for each experiment, four or five beakers were collected from each pipe. The conductivity of the fluid in the beakers is measured immediately after the experiment with a handheld conductivity meter. Samples from each of the supply tanks are also analyzed for conductivity values.

Figure 1. Views of the supply tanks (left image) and the southeast effluent tank (right image) for the single-joint experiments.

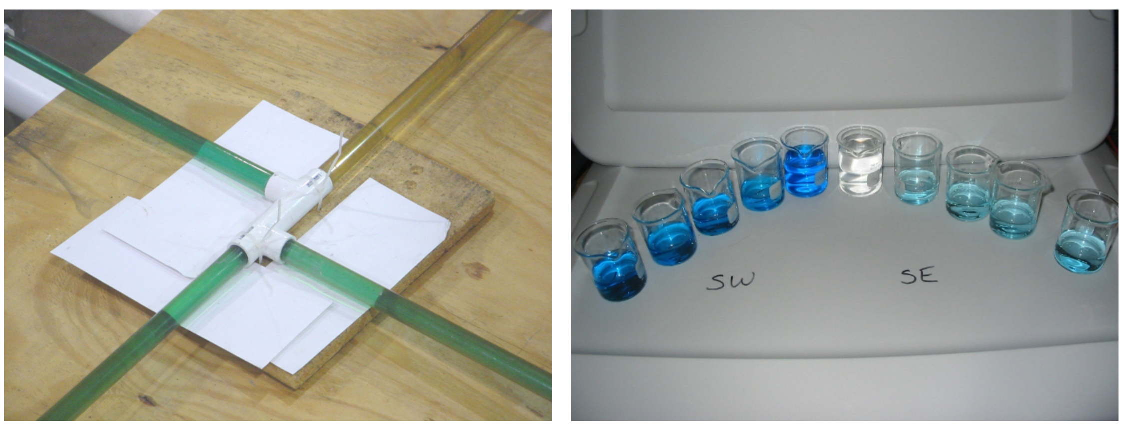

Figure 2. Detailed view of a double-T joint experiment in progress (left image) and beakers holding samples taken from the southwest and southeast effluent pipes (right image).

NETWORK SETUP

The scale model pipe network design is modular, yielding a flexible system allowing relatively easy changes in configuration. Department 6115 maintains laboratory space in the Randolph Building near the Albuquerque airport. A large high bay space was made available there for fabrication and operation of this model water distribution system. Additional facilities there include computers, data logging, sample prep and wet lab areas and fabrication shop facilities and offices.

The scale model network was constructed using ½” diameter transparent PVC pipe. The junctions, valves and other connectors were also constructed of ½” diameter PVC, but these components are not transparent. A simple, square network design was used as shown in Figure 3 to complete the network model. There are nine cross-joints in the center of the network. The distance between each pair of cross-joints is 36” or 72 pipe diameters. This sizing allows for complete mixing along the length of the pipe between each cross-joint. A valve is located at the center of each pipe connecting the cross-joints as well as in the pipes connecting the cross-joints with the valves on the outside of the network. These valves can be opened to control the demand out of the pipe or for insertion of a sensor or for connection of a different pipe segment. These valves are not used in the experiments discussed in this report.

Diagnostics included overall visualization using available video cameras. Pressure, flowrate, and contaminant concentration (water conductivity) were monitored and logged. In-line conductivity meters and flow meters were built into the network. The locations of these are shown in Figure 3 and close-ups of these two components are shown in Figure 4. Tanks are used for both the supply of tracer water and fresh water as well as for receiving the effluent at the downstream end of the experiment (Figure 5). The tracer and fresh water are brought into the system using a pair of pumps at the upstream end of the experiment. A differential manometer is used to equalize the pressure between the two input lines (fresh and tracer). Close up views of the manometer and one of the pumps are shown in Figure 6. An overview photo of the entire network is shown in Figure 7.

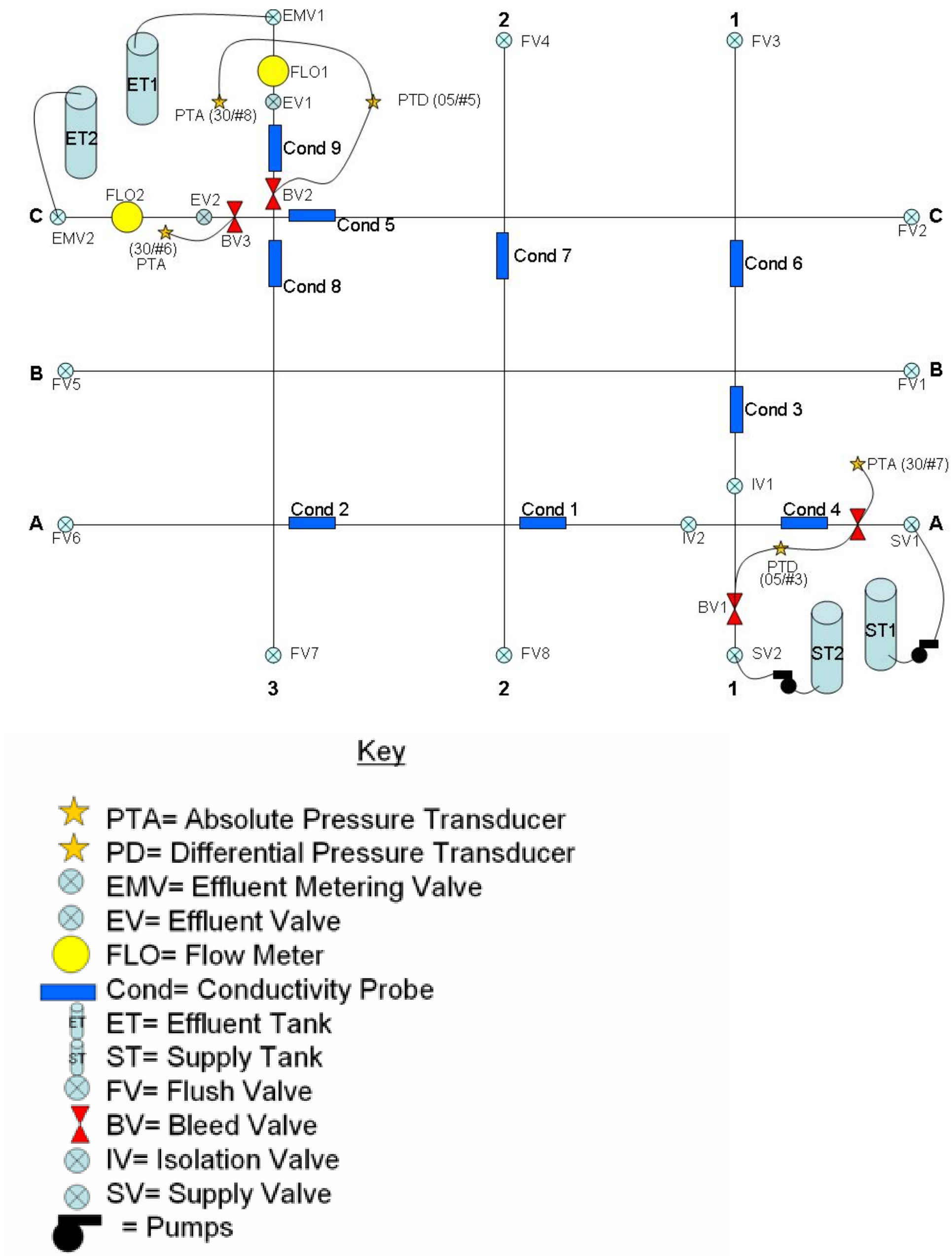

Figure 3. Experimental scale network layout

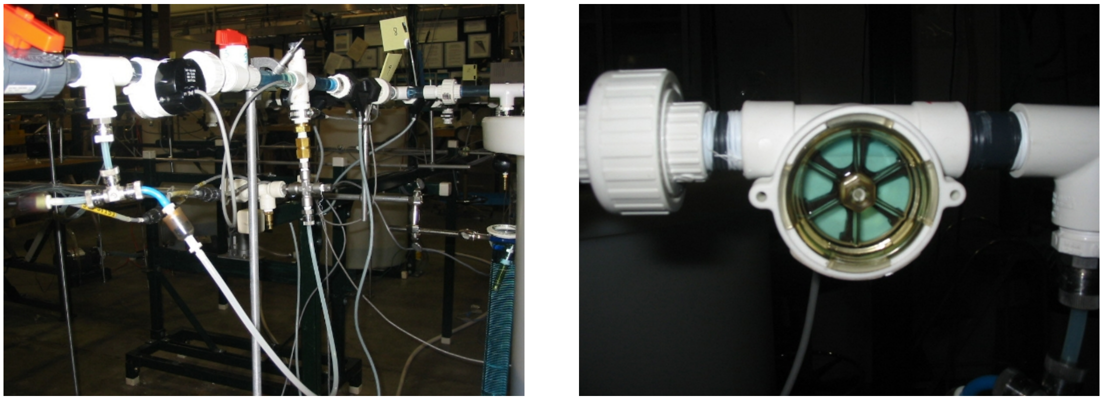

Figure 4. Detailed view of components in the network: FLO1 and COND 8 in the left image and FLO1 in the right image

Figure 5. Detailed views of the supply tanks (ST-1 and ST-2) in the left image and a view of the effluent tanks ET-1 and ET-2 in the right image.

Figure 6. View of supply differential manometer from above ST1 (left image) and ST1 and one of the supply pumps and the side of ST1 (right image).

Figure 7. Overview photo of scale network constructed in the laboratory

LABORATORY EXPERIMENTS

Experiments were conducted on both the single-joint and the network models constructed for this project. Seven different single-joint experiments and one full system run with all steps documented were completed. Many other tests were run in order to calibrate flow meters and check and/or recalibrate conductivity probes.

SINGLE-JOINT

The mixing of two fluids at a pipe junction under turbulent flow regimes is a complex phenomenon. The majority of hydraulic modeling software used by water utilities (i.e., the hydraulic solver and the solute transport formulation within EPANET) assumes that at each junction the fluids are perfectly mixed and the mass of any solute leaves the junction in the downstream pipes in proportion to the amount of water leaving the junction in those pipes. This assumption may not be valid in all cases. In order to evaluate this assumption, multiple experiments were performed in which mixing within the two pipe joint configurations described previously (i.e. "cross-joint" and "double-T") was observed and measured.

These experiments used different pipe joint configurations and varied pipe diameter and inlet flow rates in order to characterize the effect of scale (i.e. Reynolds number) on mixing. For each scenario, water was pumped into the joint through two inlet pipes, one conducting clean water and the other a solute (NaCl) concentration, the flow rates within each inlet pipe being equal. Solute concentrations were monitored within the two outlet flows to determine the amount of mixing within the joint. A schematic of the experimental setup is shown below in Figure 8. As mentioned above, the solute line was also marked with a blue dye (Warner-Jenkinson FD&C Blue No. 1).

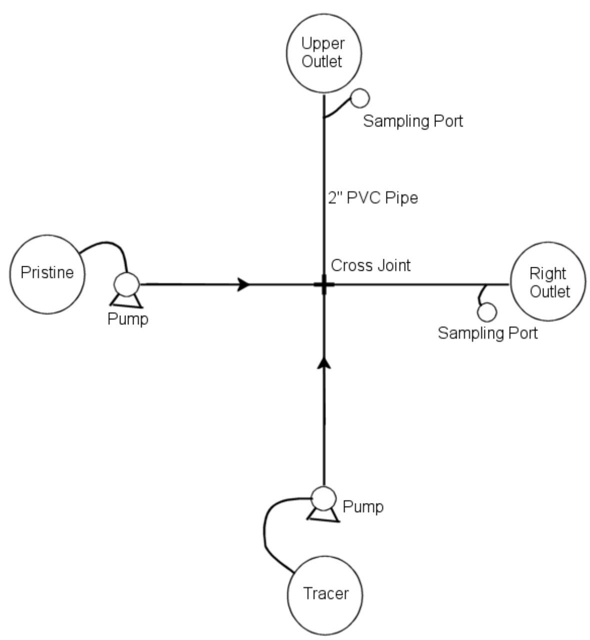

Figure 8. Experimental setup for cross-joint scenario.

Results from these experiments verified that EPANET's (Rossman, 2000) perfect-mixing assumption is overly simplistic. As an example, Figure 9 shows sampled concentrations for the two outlet pipes shown in Figure 8. This cross-joint experiment was constructed from 2 inch diameter PVC pipe with flow velocities that gave a Reynolds number of 44000. For the cross-joint scenarios, mixing was between 20-40%, while mixing for the double-T scenarios ranged from 60% to nearly 100%, though perfect mixing (i.e., 100%) was never achieved.

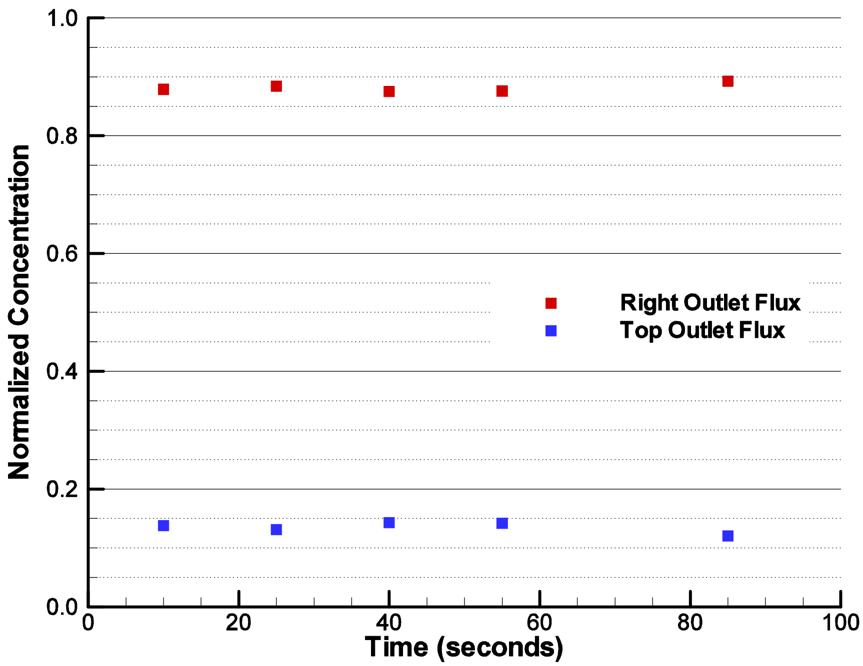

Figure 9. Normalized tracer concentrations from 2 inch cross-joint experiment.

The single joint experiments are summarized in Table 3 and the results of these experiments are shown in Figure 10. The information in Table 3 provides the type of single joint junction used (double-T or cross-joint), the pipe diameter, the Reynolds number at which the experiment was run, the normalized concentration, or mass (M/M_0) of salt solution, the average fluid velocity within the pipes and the number of pipe diameters between the two T junctions in the double-T experiments. These distances were chosen to range from two to five times the pipe diameter.

Table 3. Single-Joint experiments and average conductivity measurements.

Expt. Number	Junction Type	Pipe Dia. (in)	Reynolds Number	SW Cond Avg. (M/Mo)	SE Cond Avg. (M/Mo)	Average Velocity (m/s)	Pipe Dia between T's
1	Double-T	2	43799	0.675	0.257	0.766	2.625
2	Double-T	2	10917	0.608	0.369	0.192	5
3	Double-T	2	44278	0.628	0.351	0.771	5
4	Double-T	1	21575	0.529	0.473	0.757	5
5	Double-T	0.5	42855	0.570	0.394	3.000	5
6	Cross	2	44111	0.871	0.127	0.781	
7	Cross	0.5	42885	0.757	0.214	2.983	

Figure 10 shows the relative concentration of the solute for each of the downstream pipes. The X-axis values in Figure 10 correspond to the experiment number in the left hand column of Table 3. If the experiment produced perfect mixing in the joint, the red and blue squares would both lie on the 0.50 M/M_0 value as denoted by the dash-dot line in Figure 10. Figure 10 shows that the cross-joint configuration results deviate the most from the perfect mixing assumption. Figure 10 also shows that, in general, the smaller the number of pipe diameters between the two T junctions in the double-T experiments, the larger the deviation from perfect mixing.

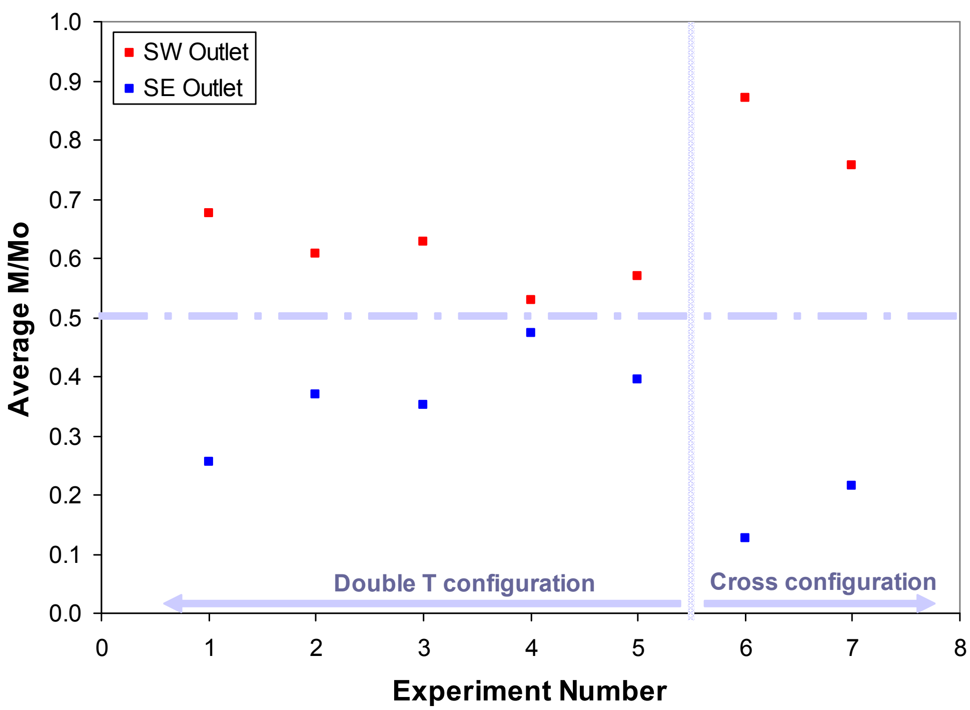

Figure 10. Summary of single-joint experimental results.

NUMERICAL MODELING

The current implementation of the US EPA's water distribution system model EPANET assumes complete mixing of aqueous solute concentrations within all water network intersections (i.e. pipe joints). This assumption is likely adequate for simplistic pipe joints (e.g. two inflowing pipes and a single discharge pipe). However, for more complex junctions (e.g. cross-joints or closely spaced double-T intersections with two inflowing and two discharge pipes), the experimental results show that water does not completely mix, and therefore, that EPANET's complete-mixing assumption is overly simplistic.

These experimental results are utilized to validate 2D and 3D numerical simulations of turbulent pipe flow through a cross-joint configuration. Simulations were run using the LES (large eddy simulation) formulation for incompressible flow with the Navier-Stokes equation within MPSalsa (Shadid et al., 1999), a 3D massively-parallel, finite-element turbulent flow and reactive transport code developed at Sandia National Laboratories. The 2D, numerical simulations were run using the geometry shown in Figure 11; this is a direct simulation of experiment number 6 in the previous section.

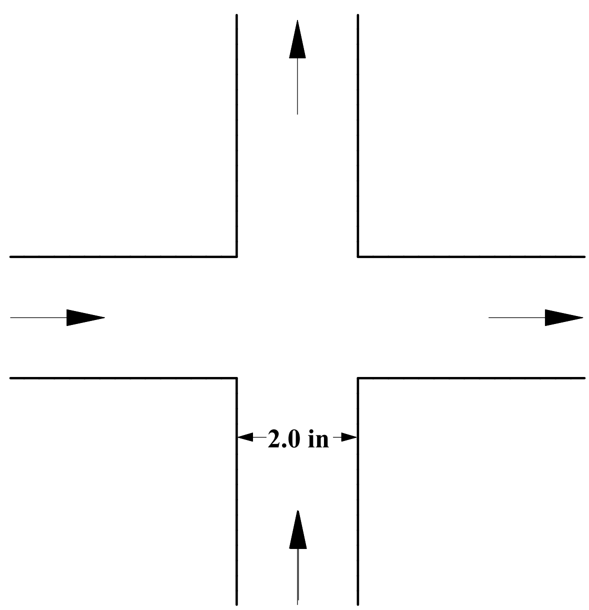

Figure 11. Schematic of 2D geometry.

For this scenario, solute was injected through the lower or southern boundary condition while clean water entered from the left or west. Figure 12 illustrates normalized tracer concentrations within the 2D turbulent flow field while Figure 13 shows flux-averaged concentrations at the two outlet boundary conditions over 20 seconds of simulation time.

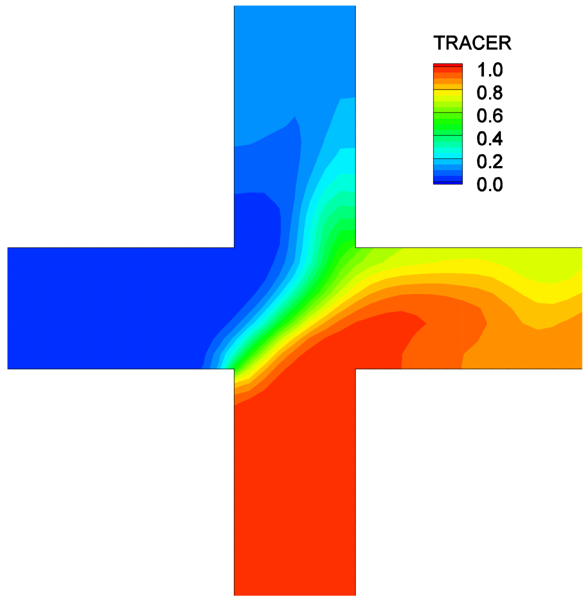

Figure 12. Normalized tracer concentrations within the 2D flow field.

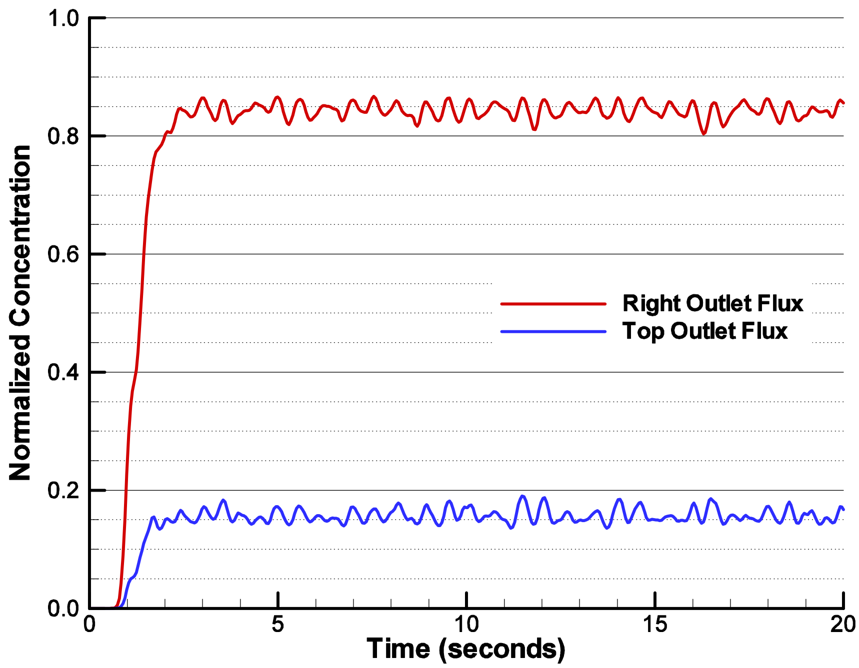

Figure 13. Flux-averaged concentrations at 2D outlet boundary conditions.

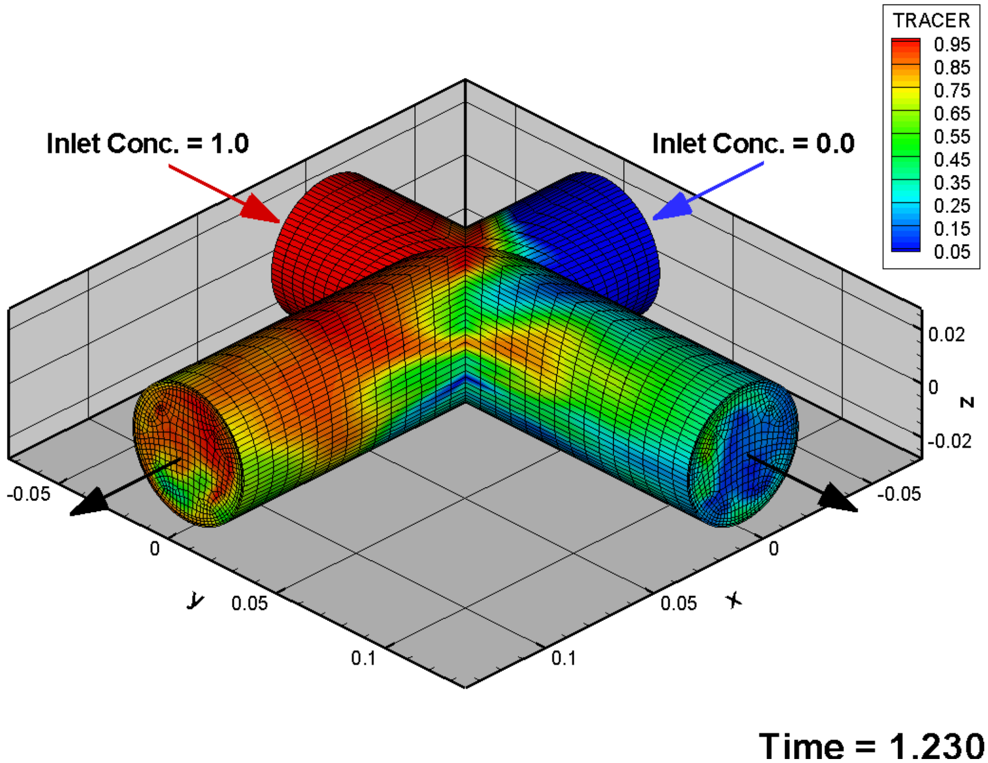

Figure 14. Normalized 3D solute concentration at time = 1.23 seconds.

The 2D simulation results for experiment number 6 match the observed experimental results very well (compare simulated concentrations in Figure 13 with observed concentrations in Table 3). More recent 3D simulations of the same experiment are shown in Figure 14.

In 3D, the simulation duration of 1.3 seconds is much shorter than the 2D time due to increased computational complexity. To generate the 1.3 seconds of high-fidelity turbulent flow and transport simulation in 3D, approximately 12 days of computation on 128 processors were required. The preliminary results for this 3D scenario, shown in Figure 15, demonstrate that, on average, the 3D simulation overpredicts the mixing observed in the cross-joint experiment by 5-10%. Additional simulations of these experiments will continue (under other funding sources). The focus of this additional research is to improve the accuracy of turbulent flow within this scenario with the goal of better matching experimental results.

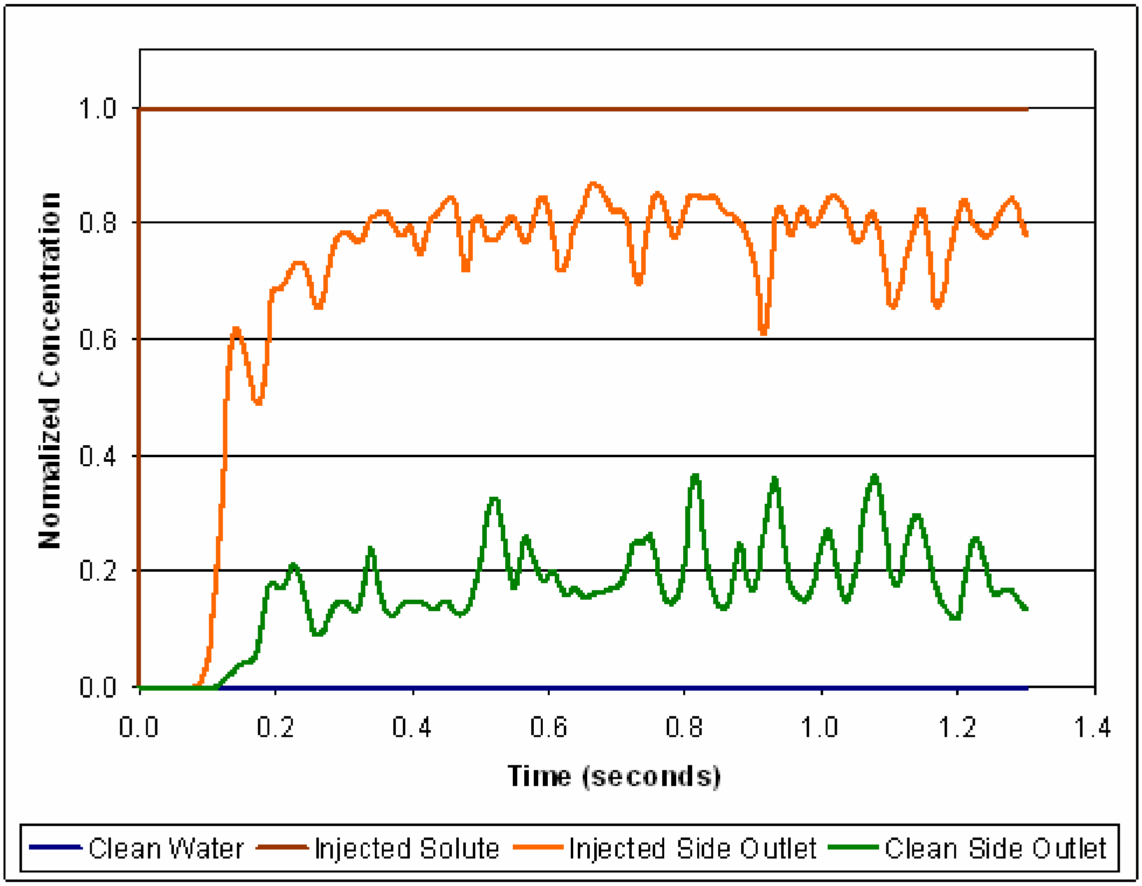

Figure 15. Inlet and outlet concentrations for 3D simulation. Injected Side and Clean Side correspond to right side and top in Figure 12, respectively.

NETWORK

For experiments conducted in the scaled water distribution network, sampling of the tracer was performed using in-line conductivity meters, not using hand samples as was done in the single-joint experiments. The tracer used in the network experiments was essentially the same as that used in the single-joint experiments: NaCl solution mixed with a blue dye. Conductivity values measured by these meters were recorded in real time by a data logging system. This system was connected to several computers and allowed for the real-time visualization of both conductivity values and flow rates as measured with the different sensors. Views of the real time data acquisition on the computers connected to the data loggers are shown in Figure 16.

Figure 16. Close up views of the data acquisition system. The data loggers and a printer are on the top shelf in the left image, above the monitors for the different computers. The right image shows real-time conductivity data being recorded and displayed on the computer monitor.

Several different tracer tests were completed in the network system. Some of these were performed in order to test the operation of the sensors, pumps, valves and data acquisition system. One of these tracer tests is fully documented in this report as an example. This example test was a “reverse” tracer test, where the entire system was filled with tracer fluid and then flushed with clear water. The steps of this tracer test are detailed in the time line presented in Table 4. The entire test sequence took more than one hour to complete. The locations of the different valves, conductivity meters and flow meters discussed in Table 4 are shown in the schematic in Figure 3 above.

Table 4. Run log for reverse tracer test

Etime (mins)	Conditions/Objectives	Action	Response	Observations
0	Network full of tracer; all valves closed; both pumps running			System partially pressurized; conductivity probes all read. Ignore graphs for next
0 to 1.638		Record not clear: SV1 and SV2 probably both opened and closed to prepare for purge of tracer	Pressures in system rise. Manometer->+	Tap water begins to dilute tracer in COND_4. Decide to run both pumps to simulate earlier cross tests but to get network back to pure tracer status first.
2.23		Open EV1 and EV2 with only SV1 opened	Pure tracer water begins flowing into effluent tanks	Flow to ET1 = 1.4gpm; flow to ET2 = 1.0 gpm; tracer water *only* flowing into network; conductivities changed initially as all diluted tracer purged from system.
4.6		Open SV2	Tap water and tracer mixing at first cross	Tap water beginning to dilute tracer in both branches. Manometer goes to ~ +0.04 psi
4.74	Equalize supply pressures	Adjust pump ST2 bypass		Manometer falls to -.1 again
4.93			Conductivities begin to fall off	CONDs_**1**, _**3** & _**9** first at same time but **1** falls off faster down to 600 while **3** levels off at ~1000 and _**9** falls off slower yet to ~875
4.95-4.98				CONDs_**2**, & _**6** are next to decrease: _**2** faster to again 600 like _**1** and _**6** to 1000 like _**3**
5.03				COND_**7** now begins to decrease
5.05				followed by COND_**8** which falls off faster to the 650 range
5.08				And then finally COND_**5**
5.8		Adjust bypass on ST1 pump	Manometer returns to +- .05 psi	Conductivities begin to increase again

9.31		Close SV1	Manometer falls to -.1 again	Tap water *only* now flowing into network.
9.45			Conductivities again begin to decline	CONDs**_1**, **_3** & **_9** first at about the same time but **1** has less to decrease to tap concentration (425 µS) while **_3** falls to the same level in the same time (9.54 mins); **_9** falls off slower reaching 425 µS only by 9.672 mins,
9.54				CONDs**_2**, & **_6** are next to decrease: **_6** reacted slightly sooner but both reach tap concentration at 9,67 mins
9.59				COND**_7** now begins to decrease,
9.64				followed by COND**_8** and COND**_5** again
10.00	All probes are reading tap concentration			
11.03 – 11.57	Flow rate to ET1 greater than to ET2	Turn EMV1 down	Reduce ET1 flow to 1 gpm	No effect in conductivities noted.
15.24 – 17.21	Purge dead branches of tracer concentrate	Open bleed valves sequentially, starting with BV1 and proceeding counter clockwise.	Perturbations in pressures induced	Starting with BV1 and proceeding counter clockwise. Tap water moves/diffuses slowly into feed pipe from ST1. COND_4 decreases in steps
18.39	Tap water still flowing	Open SV1	Tracer flows into network	Conductivities begin to increase. Level out by 19.5 mins
20.3	Conductivities leveled out	Adjust pump bypass valves to increase tap flow	Manometer moves from avg +0.01 to -0.18	Less tracer and more tap water flowing into network, Effect quite significant and immediate to lower conductivities again
20 to 21			Supply flowrates change	Subtle change seen in relative slopes of supply tank volumes over time
29.65	Conductivities leveled out. Check effect of reducing flow to ET1	Trim EMV1 down in steps	EF1 -> 0.75 gpm	No apparent effect on conductivities
31.29			EF1 -> 0.5 gpm	No apparent effect on conductivities

32.5	No flow to ET1		EF1 -> 0.0 gpm	After short delay, conductivities all fall off slightly
34				Impact on flow from ST2 greater than ST1
38.0				Abrupt rise in conductivities to former levels for minute. Not known the reason for this
39.6				Conductivities return to lower levels again
42.85		Open EMV1 again	EF1 returns to 1 gpm	Conductivities return to higher levels
62.85 and 62.93	ST1 and ST2 both still open; pumps still on	Shut EMV1 and then EMV2	All flow out of network stops	Pressures rise in system
63.25				Back flow of tap water into ST1 feed pipe causes level in COND_4 to drop off.
63.42		Close ST2 and ST1; turn off pumps	Back flow stops	Noise levels on conductivity signals reduced

The following figures show different time periods of the test documented in Table 4. They were chosen to highlight different aspects of the tracer test. The time scale (in minutes) on the X-axis of the following figures corresponds to that in the left column of Table 4.

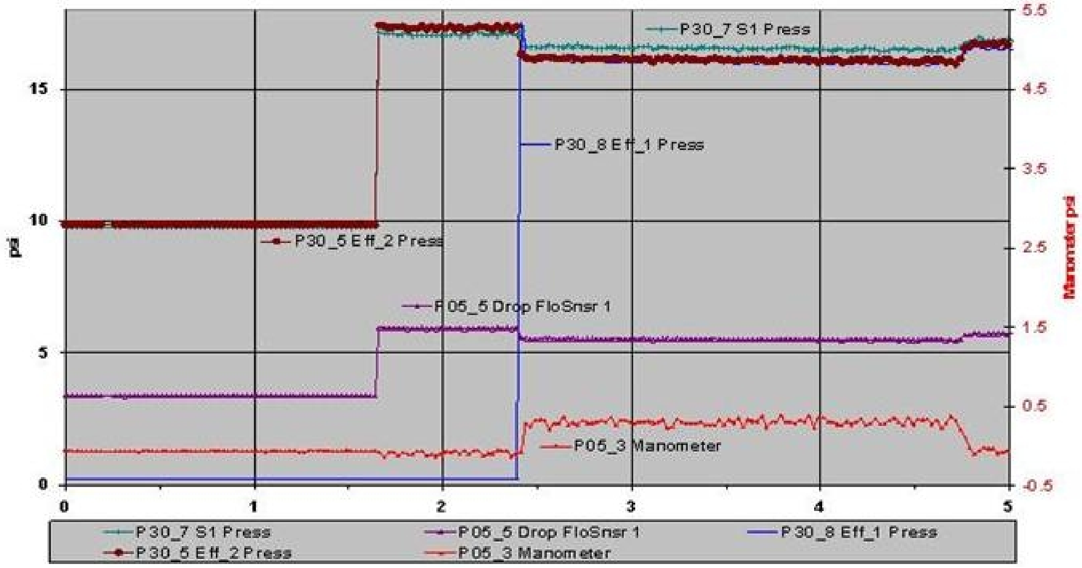

Figure 17. Response of pressure meters and manometer to start of flow.

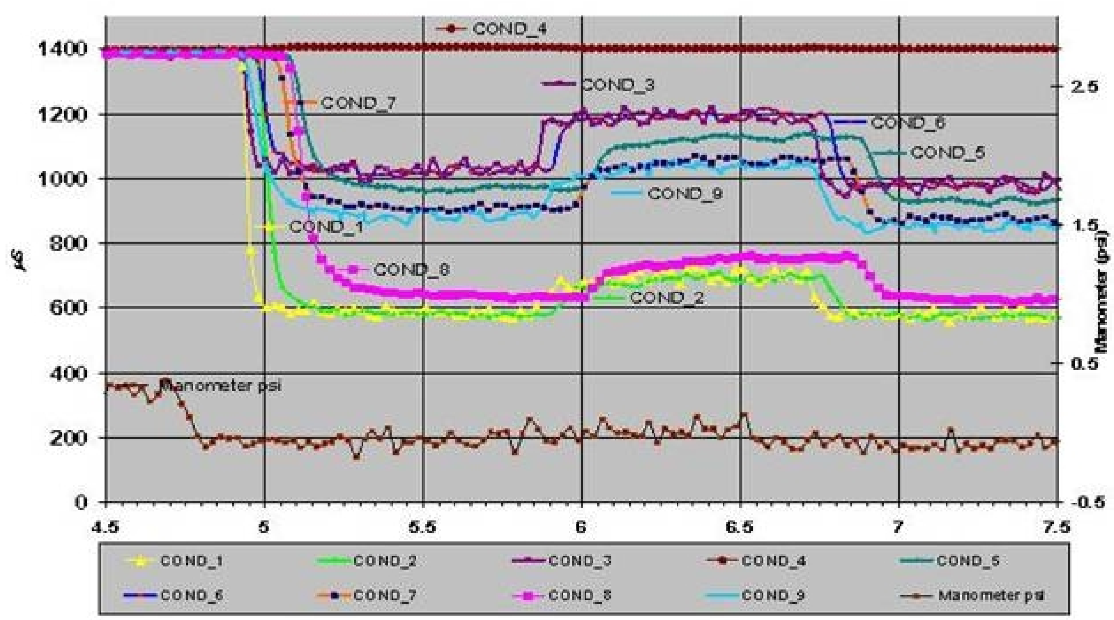

Figure 18. Response of conductivity meters to initial dilution sequence.

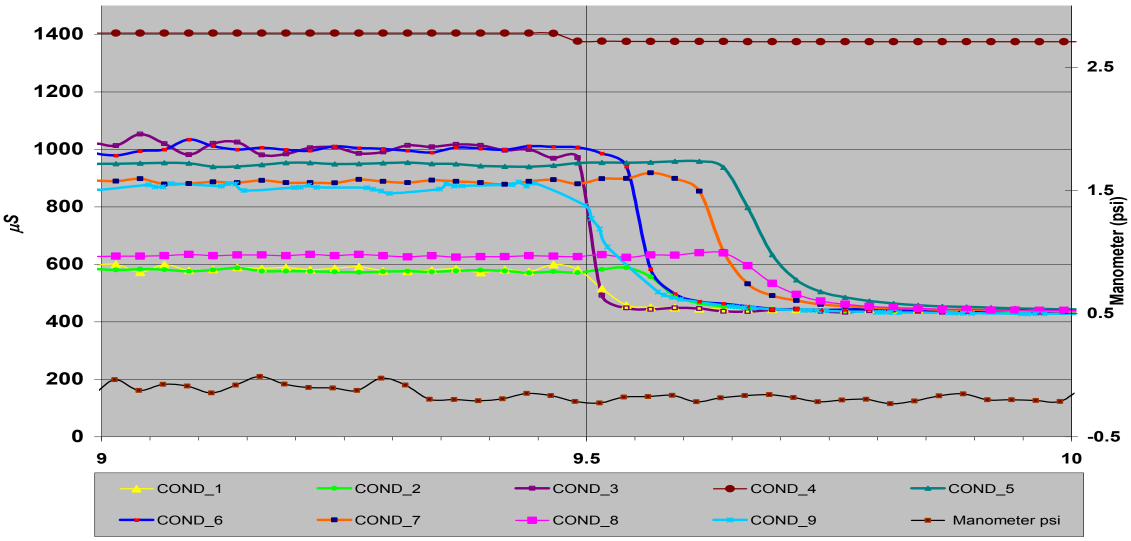

Figure 19. Conductivity and manometer responses to purging of the remaining tracer.

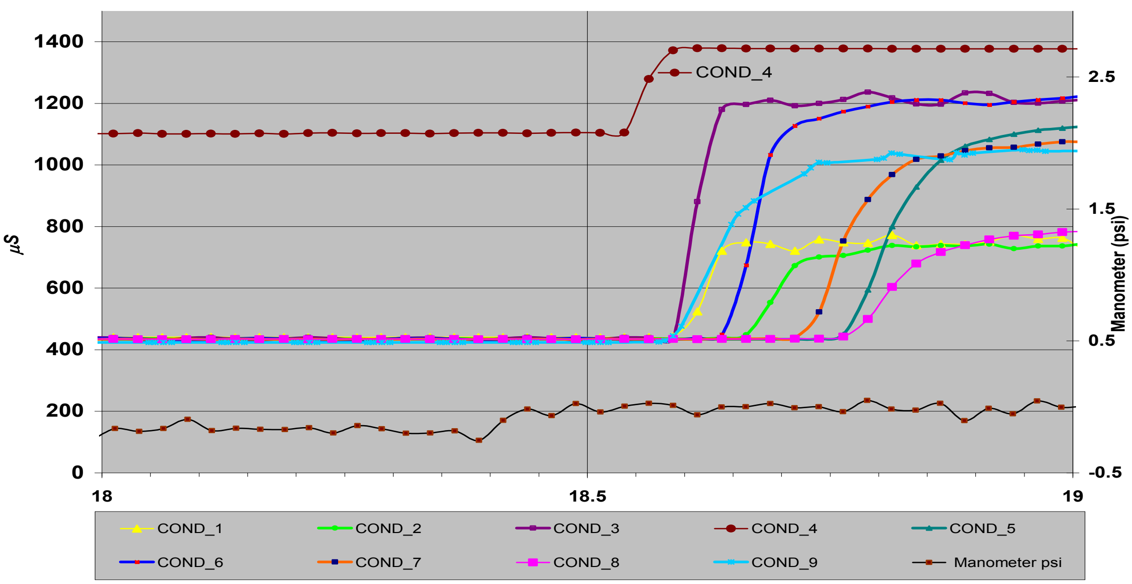

Figure 20. Conductivity response to reinjection of tracer from Supply Tank 1 (ST1)

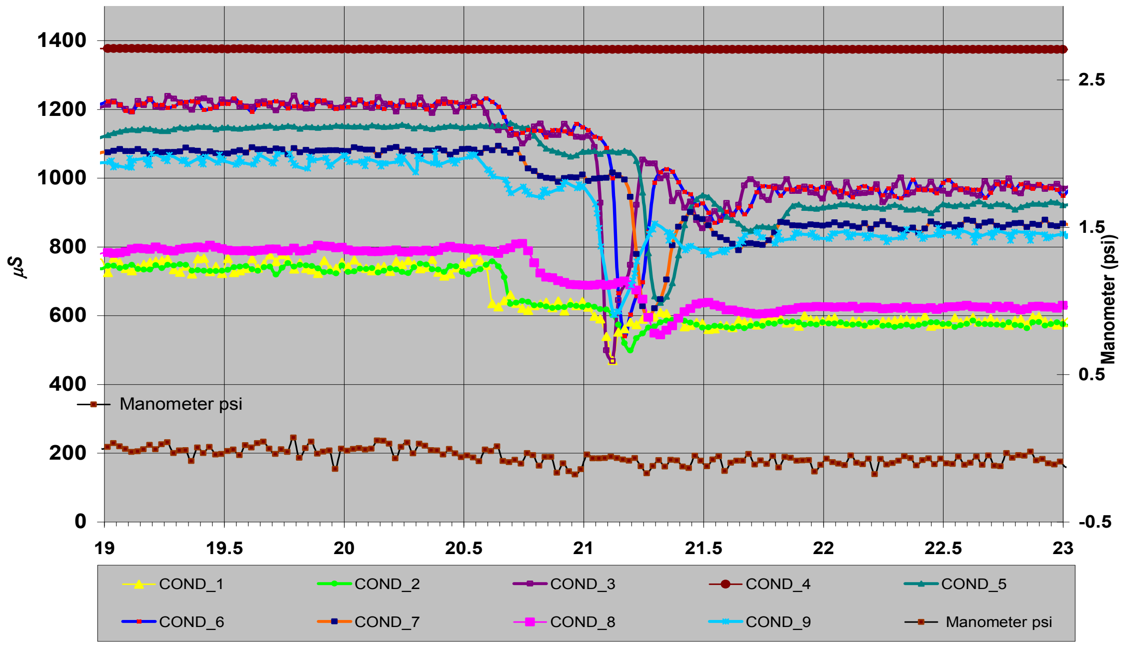

Figure 21. Conductivity response to adjusting bypass pump that injects more fresh water into system.

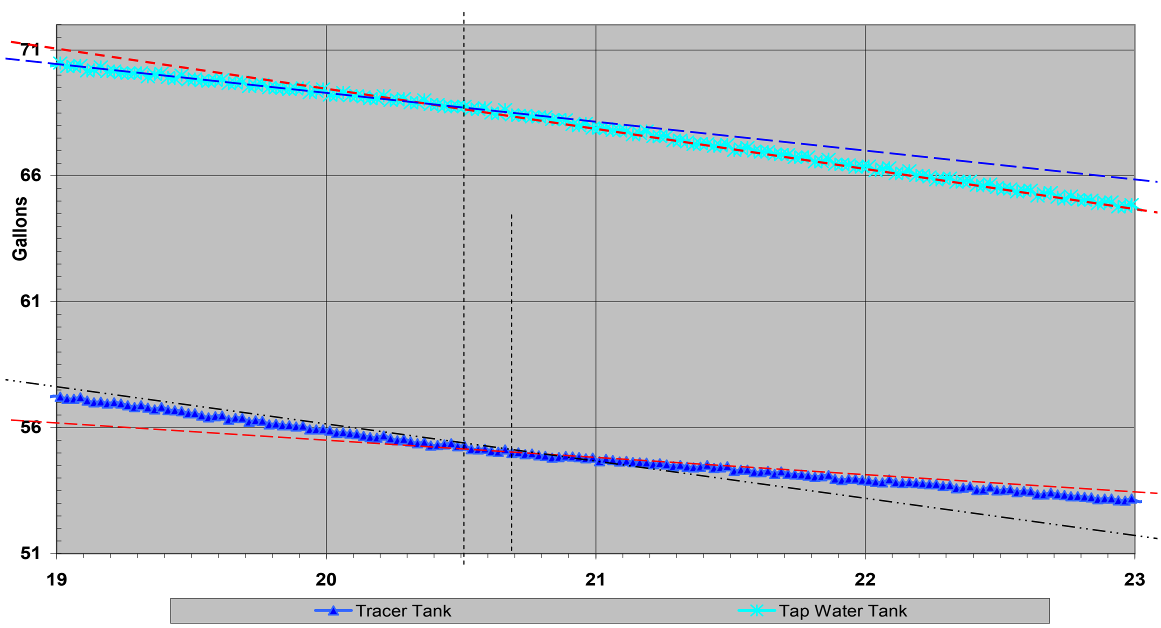

Figure 22. Subtle change in supply tank inflows due to adjustment of bypass valve. Note change in slopes near 20.5 minutes.

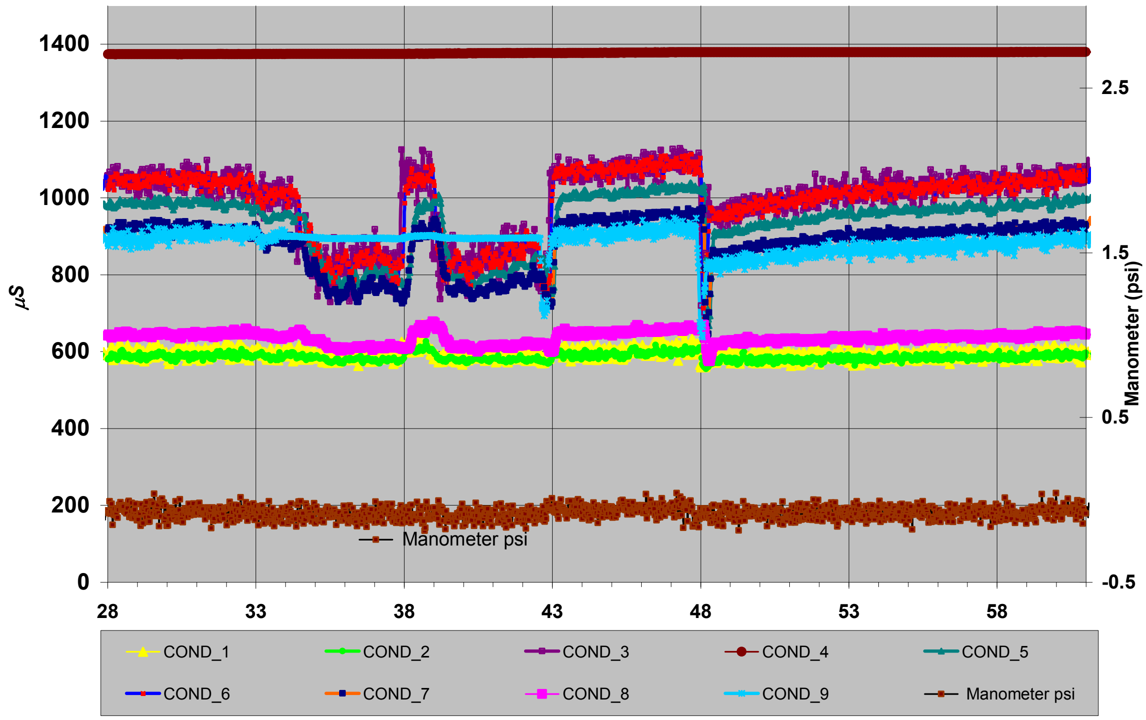

Figure 23. Response of conductivity values to flow rate reduction

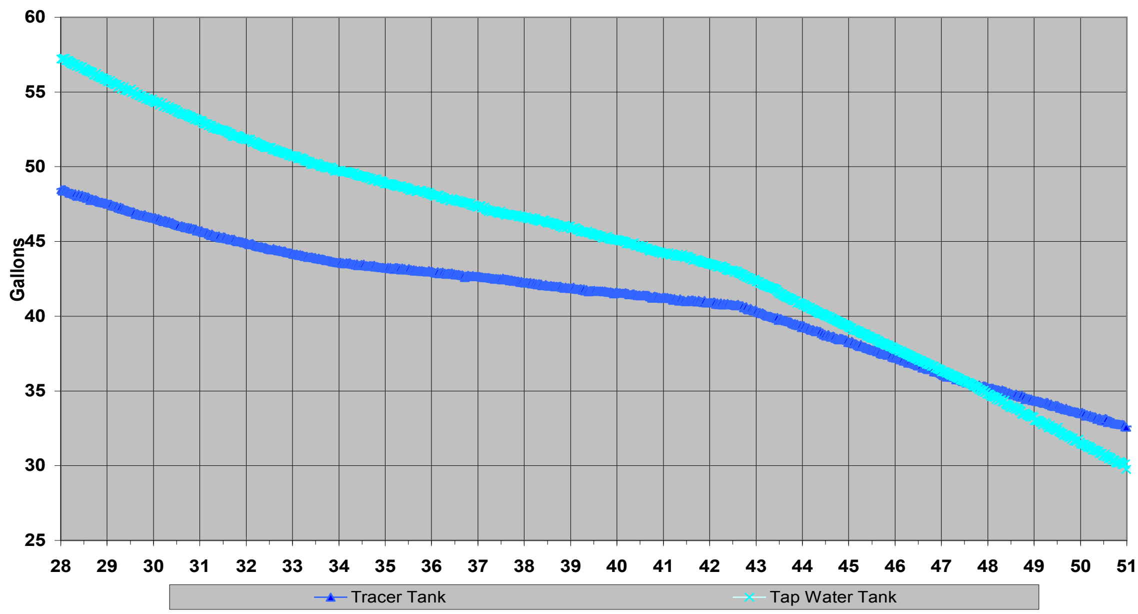

Figure 24. Effects of effluent rate adjustments on supply flow rates.

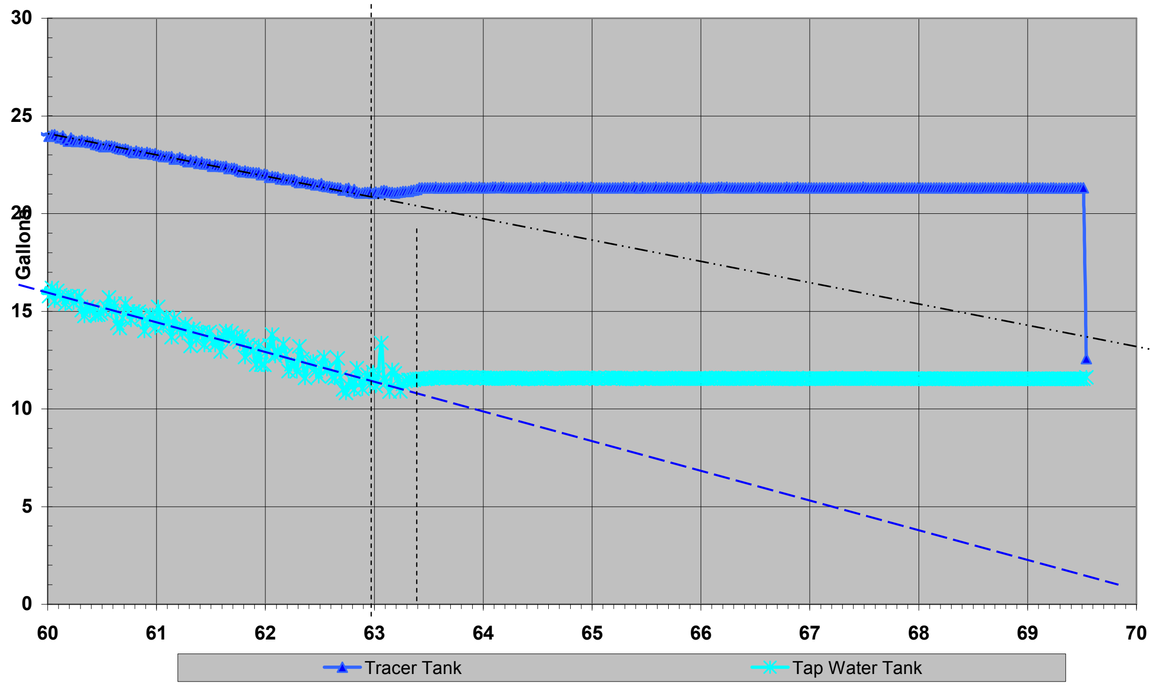

Figure 25. Supply tank levels prior to and after the system shutdown near 63 minutes.

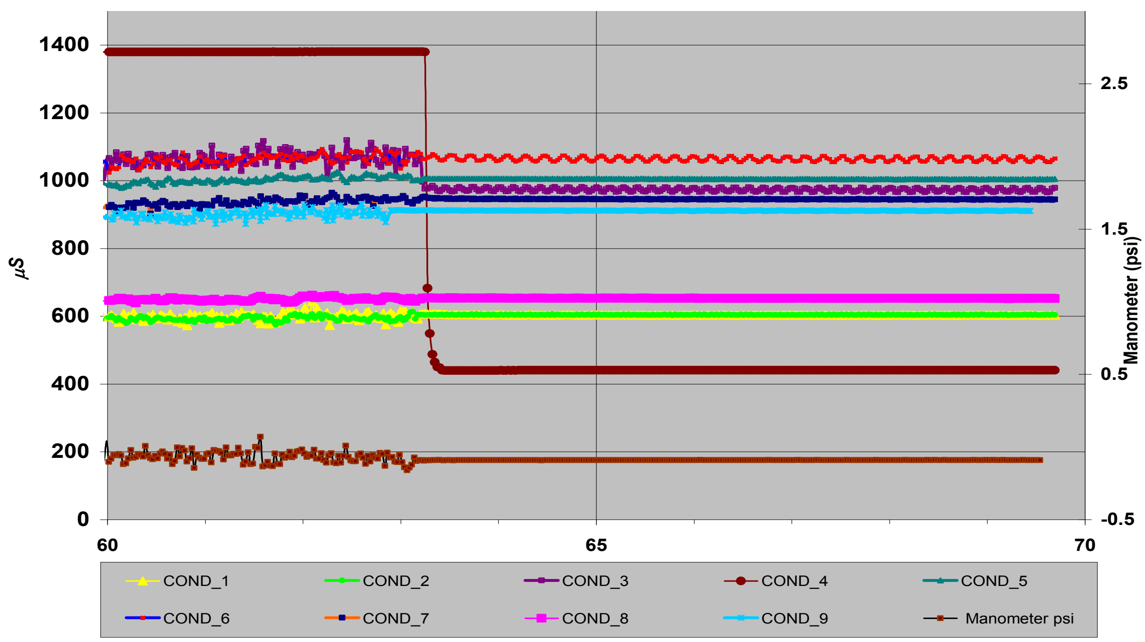

Figure 26. Response of conductivity and manometer values to system shutdown.

The data in Figures 17 through 26 show that show that the scale model water distribution system can be operated to provide detailed information on the flowrates and contaminant concentration at various points in the network. The data also show that an injected contaminant moves through the network in a matter of seconds. These results show that useful information can be obtained from running experiments in both the forward (adding tracer to an initially clear network) and reverse (adding clear water to a network with a uniform and non-zero tracer concentration) modes.

SUMMARY

This was a small LDRD directed towards demonstrating the feasibility of using a scale model to provide validation data for computational models of water distribution networks. Several important accomplishments were made:

1. Simulations were performed supporting the experiment design. These started with a simple pipe "cross" junction and were extended to a small pipe network. The simulation results guided the experiments in terms of where measurements were needed and what range of flow conditions should be covered.
2. Single junction experiments using cross-joint and double-T configurations were completed. Data showed incomplete mixing in every case, with the double-T configuration giving better mixing than the cross-joint configuration. These results point out a weakness in the standard numerical models that assume complete mixing at every junction.
3. 2D and 3D numerical simulations of one of the cross-joint experiments were performed. The 2D simulations gave good agreement with the experiment but the 3D simulations overpredicted mixing by 5-10%.
4. The pipe network built and tested. This 20:1 scale model was fabricated with 1/2 clear PVC pipe to allow optical measurements of, for example, dye transport and mixing in the pipe network. Much of this work was performed by UNM students brought in on this program.
5. Pressure, flow, and mixing data were acquired in the pipe network.
6. A computational model of the network was created but not yet validated

NOMENCLATURE

D	pipe inner diameter
Q	volumetric flow rate
Re	Reynolds number
U	average velocity in pipe

Greek Symbols

ν	kinematic viscosity
τ	time scale

Subscripts

lab	scale model
full	full scale

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